4. Nuclei and Radioactivity

(revised 20 Sept 2005)

Paradoxes and puzzles

1. This book is radioactive. If you are reading this on a computer screen, don't take too much solace. Your chair is probably more radioactive than the book would be.

2. If you aren't radioactive, then you are dead. And have been so, for a long time.

3. The United States Bureau of Alcohol, Tobacco, and Firearms tests wine, gin, whisky, and vodka for radioactivity. If the product does not have sufficient radioactivity, it may not be legally sold in the United States.

4. Of those killed by the Hiroshima atomic bomb, the best estimate is that fewer than 2% died of radiation-induced cancer.

Those anecdotes are all true, and yet they surprise most people. That reflects the confusion and misinformation that pervades the public discussion of radioactivity. I hope that when you finish this chapter, you can come back and read those four anecdotes, and say, "of course."

What is radioactivity?

Radioactivity is the explosion of the nucleus of the atom. The key feature of radioactivity that makes it so fascinating is that the energy released is enormous – at least when compared to typical chemical energies. The typical energy release in the explosion of one nucleus of one atom is about million times greater than in a chemical explosion of a single atom.

I said the energy released is "enormous." Let me put that in perspective. It is enormous for a single atom --

In chapter 2, we discussed molecules (such as H_2O), the atoms they are made from (such as H and O), and we mentioned that deep within the atoms is the much smaller nucleus. We'll review some of that now, and discuss the nucleus in more detail.

As I said in chapter 2, the atom has a radius of about 10^{-8}. That used to be considered so small that we would never see one, but a device called a "scanning tunneling microscope" can pass over individual atoms, feel their shape, and then present that on a computer screen in the form of an image. Individual atoms can be picked up and placed at new locations. In the following figure we show 35 xenon atoms arranged to form the letters

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"IBM" on the surface of a nickel crystal. The atoms of nickel are not visible (they blur into a smooth background).
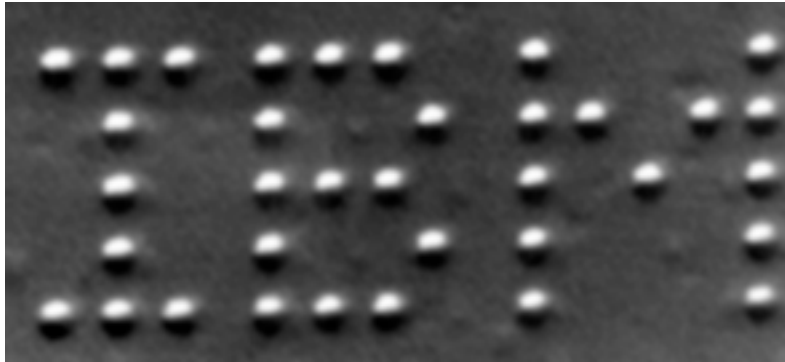
Figure: atoms

The letters "IBM" written by arranging individual Xenon atoms on the surface of a nickel crystal. The atoms were manipulated and photographed using a "scanning-tunneling microscope." This work was done by a team led by Donald Eigler. Guess which company they worked for.

To put the size of an atom in perspective, consider the following examples: a human hair has a thickness of about 200,000 atoms, and a human red-blood cell has a diameter of about 10,000 atoms. These numbers are big, but not huge. I didn't have to use scientific notation. So atoms are small, but they are not infinitesimally small.

Each atom consists of a cloud of electrons with a tiny nucleus in the center. The nucleus has a radius of about 10^{-13} cm, which means it is 100,000 times smaller than the atom itself. To visualize this ratio, imagine that an atom were enlarged until it was the size of a baseball or football stadium (300 meters). Then the nucleus, similarly expanded, would only be the size of a mosquito (3 mm). Since its linear size is 10^{-5} that of the atom, then its volume is 10^{-15} of that of the atom (since you calculate volume by taking the cube of the linear size). That's like the volume of the stadium compared to the volume of the mosquito. This enormous disparity often gives rise to the statement that the atom is mostly "empty space." Some could argue, however, that the space isn't really empty; it is filled with the electron wave. We'll talk more about that in Chapter 12, on quantum mechanics.

Yet even though it has only 10^{-15} of the volume of the atom, the nucleus contains more than 99.9% of the mass of the atom. The nucleus is very small, but very massive. That was not predicted; try to imagine the surprise and disbelief of scientists in 1911 when

Rutherford discovered this incredible fact and announced it. It seems completely implausible. But it is true.

Within 20 years of Rutherford's discovery, we learned that the nucleus itself was made up of even smaller pieces. The most important of these are protons and neutrons:
>**Protons** weigh almost 2000 times as much as an electron, and have the same magnitude of electric charge, but opposite in sign. (We'll discuss the sign of the charge in Chapter 6. Electrons, by convention, have negative charge, and protons have positive charge.)
>**Neutrons** are similar in mass to protons (they are actually about 0.3% heavier), but have no electric charge, i.e. they are "neutral" –hence their name.

So here is the basic picture of the atom: it has a very small nucleus, made of protons and neutrons. Surrounding this is a relatively large volume occupied by electrons. But most of the mass is in the tiny nucleus. The nucleus of an atom weighs almost exactly the same as the entire atom itself, since the electrons are so light.

Quarks and gluons

Scientists love to deconstruct – so it is natural for them to wonder whether protons and neutrons are made of smaller objects. The answer was uncovered in the last few decades of the 20th century: particles we call **quarks**[1], and a variable number of lightweight **gluons** that hold the quarks together (that's why they are named after glue). There are two types of quarks in these particles, called *up* quarks and *down* quarks.[2] A proton consists of two up quarks and one down quark. This fact is often written in a form that looks like an equation (since it has an equal sign):

$$p = uud$$

where p stands for the proton, u for the up quark, and d for the down quark. But this isn't really an equation; there are no numbers that you could put in to make the two sides equal.

A neutron consists of two down quarks and one up quark, and that is written in an analogous way:

$$n = udd$$

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[1] The name "quark" was proposed by Cal Tech physicist Murray Gell-Mann, who found the term used in James Joyce's novel *Finnegan's Wake*.

[2] The words *up* and *down* do not refer to directions in space. They derive from an analogy with electron spin directions, which could be up or down. But it is only an analogy.

What are quarks and gluons made of? We don't know, but some people believe they are made of the ultimate elementary particle called a *string*. That's what *string theory* is all about. There is no strong evidence supporting string theory.

What are electrons made of? Not quarks. In fact, an electron appears to be very much like a light quark itself. Just as for quarks, it is possible that electrons are made of strings. We don't know. Maybe they are made of nothing smaller. Maybe they are really the final and truly *elementary* particles. We don't know.

In summary:

Matter is made of molecules (e.g. water is made of H_2O)

Molecules are made of atoms (e.g. H_2O = hydrogen and oxygen)
Atoms are made of electrons orbiting a nucleus
Nuclei are made of protons, neutrons + other light particles (e.g. gluons)
protons and neutrons are made of quarks and gluons
quarks and electrons *may* be made of strings

The number of protons in the nucleus is called the "atomic number." An atom of hydrogen has one proton in the nucleus (and one electron in orbit), and we say it has atomic number 1. An atom of helium has two protons in the nucleus and two electrons in orbit. It has atomic number 2. An atom of uranium has 92 protons in the nucleus, and 92 electrons in orbit. We say it has atomic number 92. Each element has a different atomic number. Here is a list of some of the atomic numbers of elements we will be discussing in this chapter:

element	atomic number (N_p)
hydrogen	1
helium	2
lithium	3
carbon	6
nitrogen	7
uranium	92
plutonium	94

Thus, for example, a uranium nucleus has 92 protons. That means that there are also 92 electrons orbiting a uranium nucleus.

isotopes

In addition to protons, a nucleus can have neutrons. They don't have charge, so they don't change the behavior of the atom (at least, not much), but they make the nucleus heavier. So, for example, a hydrogen nucleus always contains one proton. Ordinary hydrogen, the abundant kind, has no neutrons. But about one out of every 6000 hydrogen atoms has a nucleus that contains an extra neutron. That kind of hydrogen is called **deuterium**, or

"heavy hydrogen." (Memory trick: think of the proton and neutron in the nucleus forming a *duo*.) Water made from heavy hydrogen weighs more; it is called heavy water. Heavy water was very important during World War II in the development of the nuclear reactor. In fact, Hitler had a special plant to purify deuterium, and the Allies sent a team to blow that plant up.

Some hydrogen (about 10^{-18}, or a billionth of a billionth of ordinary hydrogen) has two neutrons in the nucleus. This kind of extra heavy hydrogen is called **Tritium**. (Memory trick: think of the proton and two neutrons in the nucleus forming a *trio*.) Tritium is the only kind of hydrogen that is radioactive. It is used in medicine and in hydrogen bombs.

Radiation and rays

Now lets return to the radioactivity, the explosion of the nucleus. A common chemical explosion (e.g. TNT) takes place when a large *molecule* suddenly breaks up into smaller molecules. In a similar way, a radioactive explosion takes place when a *nucleus* breaks up into smaller parts.

We'll begin with the most common type of radioactivity, in which a relatively small particle is thrown out from a big nucleus. It flies out like a bullet, at very high speed, sometimes approaching the speed of light. When this process was first discovered, nobody knew what was coming out. The projectiles couldn't be seen directly, but they passed through matter, and could expose photographic film. The projectiles were called "rays" – probably because of the fact that they travel in nearly straight lines. They had properties similar to X-rays, which Roentgen had discovered a few years earlier. Different kinds of rays were found, with somewhat different properties, and they were named after the letters of the Greek alphabet.[3] Some rays (e.g. from uranium) could be stopped by a piece of paper; these were called **alpha** rays. Rays with more penetration were called **beta** rays. The most penetrating of all were called **gamma** rays. (There were delta rays too – but those turned out to be the same as low energy beta rays so the term is little used.)

The old terminology has changed; instead of saying *rays*, we now say *radiation*. It is worthwhile to learn this formal terminology:

> *radioactivity* refers to the explosions of atomic nuclei
> *radiation* consists of the pieces that get thrown out in the explosion

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[3] The first few letters of the Green alphabet, printed in lower case, are α (alpha), β (beta), γ (gamma), δ (delta). The last (24th) letter is ω (omega).

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Each ray (or particle) is like a tiny bullet, so tiny that you don't feel it if it hits your body. Alpha rays and beta rays bounce off many atoms before they stop, and with each bounce, they can knock apart a molecule, or mutate a gene. The slowing bullet leaves a trail of damaged molecules along its wake. The damage is small, but if you are hit by a large number of particles, the total effect can make you ill, or even kill you. Gamma rays tend to be absorbed by a single atom, but when that happens they frequently break up the atom or even its nucleus, so secondary radiation is emitted. It is that secondary radiation that often does the most damage.

"Seeing radiation" – the Cloud Chamber: When alpha or beta rays pass through a gas, they knock electrons off atoms, creating a trail of charged particles called *ions*. If the gas has a lot of water vapor or alcohol vapor mixed in, and the gas is cool, then the water or alcohol tends to form little droplets on these ions. In essence, they form clouds along the path of the radiation. White tracks suddenly appear when an alpha or beta ray passes through a chamber set up in this way. In the image below we show some images taken in the original cloud chamber invented by Charles Wilson (for which he got the Nobel Prize in 1927). The streaks are the cloud particles along the path of the radiation.

Figure: Cloud Chamber
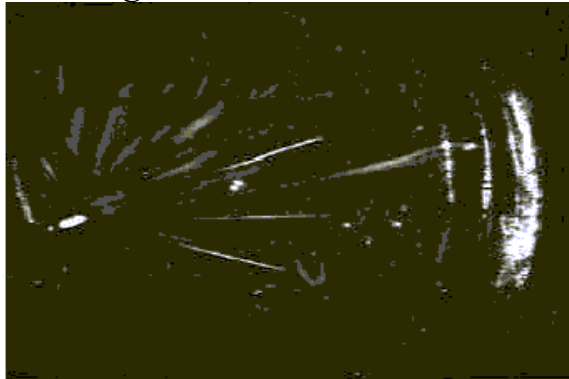
The tracks are very similar in nature to the vapor trails left behind when a jet airplane engine passes overhead. The track doesn't actually show the airplane itself, but it shows where it has passed.

A cloud chamber is a marvelous thing to watch. Radiation from a radioactive source will show short white lines of cloud particles suddenly forming along a path. The droplets are heavy, so they drift to the bottom of the chamber. Meanwhile, new paths are suddenly appearing above them. Every once in a while, a long path appears – due to radiation coming from space, known as *cosmic radiation*. The Cloud Chamber setup we use in lecture at Berkeley is shown here.

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Radiation and death: the *rem*

The biological damage done to cells when hit by radiation is measured in a unit called the *rem*. I can give you a rough idea of how big a rem is from the following example. Suppose each square centimeter of your body is penetrated by two billion gamma rays. If that happens, then the radiation dose to your whole body is approximately 1 rem.[4]

Two billion gamma rays sounds like a lot of radiation, so it might make you think that a rem is a huge amount of damage. But remember, the nucleus is very small. When it emits energy, the energy is big only in a relative sense. For example, the gamma rays entering your body will deposit their energy, and that will cause your body to warm up. But the amount of warming can be calculated; it is less than one billionth of a degree C.[5] The radiation does damage individual molecules, and that is the source of all the real danger. Most of the time, the damage can be repaired by the cells in your body. But your body is not always successful. Many people estimate that the exposure to this much radiation (1 rem to every cell in your body) will increase your chance of getting cancer by about 0.0004, i.e. by 0.04%. We'll talk more about that shortly.[6]

The term *rem* was originally an acronym[7] . Physicists will never miss a chance to honor one of their own, so it was inevitable that a new unit would be introduced: the *Sievert*[8]. The conversion is simple: there are 100 rem in 1 Sievert. If you look at modern textbooks, you'll see Sieverts used more and more often. But most public reports still persist in using the rem, so we will too. (Memory trick: the Sievert is capitalized – and it is the *big* unit. It consists of 100 of the smaller uncapitalized rem.)

Radiation poisoning

If every cubic centimeter in your body is exposed to one rem, then we say you have received a "whole body dose" of one rem. If the whole body dose is more than 100 rem, the damage done to the molecules of the cells is enough to disrupt the metabolism of the body and the victim becomes sick. This is called radiation poisoning. If you know someone who has undergone radiation therapy (to kill a cancer), then you know what the

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[4] For this example, I assumed that the gammas had energy of 1.6×10^{-13} joules each, a value defined to be 1 million "electron Volts" or 1 MeV. That is the energy that an electron would get if it were kicked off a wire that had a voltage of one million volts.

[5] The calculated value is 2×10^{-11} C

[6] In this calculation, I am assuming the "linear hypothesis." We'll discuss that later in the chapter.

[7] for "**R**oentgen **e**quivalent in **m**an" where the unit of Roentgen is the amount of radiation it takes to release a certain number of electrons per gram of material.

[8] named after Rolf Sievert, the former chairman of the International Commission on Radiation Protection.

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symptoms of mild radiation sickness are: nausea, listlessness (popularly referred to as "loss of energy"), loss of hair. The severity of the illness depends very sensitively on the dose, as the table below shows.

Whole body dose	resulting radiation illness
below 100 rem (below 1 Sievert)	no short-term illness
100 to 200 rem (1 to 2 Sievert)	slight or no short-term illness; nausea, loss of hair; rarely fatal.
300 rem (3 Sieverts)	50% chance of death, if untreated, in 60 days
more than 1000 rem (more than 10 Sieverts)	incapacitation within one or two hours. Survival unlikely

In medical terminology, 300 rem is said to be the "**LD50**" -- which stands for the "Lethal Dose" that will kill "50%" of those exposed. Memorize the following:

LD50 for radiation is 300 rem = 3 Sieverts

You will frequently hear the term *millirem* being used when people talk about radiation leakage. One millirem is one thousandth of a rem. LD50 for radiation is 300,000 millirem. The reason that I want you to memorize these numbers is that you will very likely encounter radiation in your life, maybe at a doctor's office, maybe elsewhere. You'll probably hear the term millirem, rather than rem. A dental x-ray gives, typically, a few millirem to your jaw (not to your whole body). It is useful to understand how small a millirem is.

Radiation and Cancer

Get ready for a paradox: The average dose that it takes to induce cancer is a whole body dose of approximately 2500 rem.[9] But LD50, to kill you immediately from radiation illness, is only 300 rem. So how can anyone get cancer from radiation? You might (incorrectly) think that they would die first.

The "Linear Hypothesis"

The solution to the paradox lies in the "linear hypothesis." We can't give 2500 rem to a single person without immediate death, but if we spread it out among 2500 people, each of whom will be exposed to 1 rem, then the same total damage will be done. Not one person will get radiation illness, but the same number of mutations will be induced – just

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[9] It was once thought that it took 4 times more than this, and some old books will still show the value of 10,000 rem, but 2500 rem is the current best estimate.

spread out over many people. The linear hypothesis is a fancy name for the belief that the 2500 rem, even though distributed over a large number of people, *will still cause one cancer* – not one cancer each, but one cancer total among the 2500 people.

The basis for belief in the linear hypothesis is the fact that most mutations are harmless; they may cause the cell to die, but we have lots of cells, and many of the cells can be replaced. But after 2500 rem of damage, the chances are good that a particularly bad mutation will be created in one of the victims,[10] a mutation that causes cancerous multiplication of cells.

Not all experts believe the linear hypothesis. They argue that the cell can repair minor damage, so if spread out enough, every body will be able to recover.   We know that the linear hypothesis doesn't work for radiation sickness. 1000 rem will kill you from radiation illness, but 1 rem each, spread over 1000 people, will cause no radiation illness whatsoever. Moreover, the linear hypothesis doesn't work for most other kinds of poisons, such as arsenic.

Others counter by saying that radiation sickness (and other poison) is different from cancer. Radiation illness occurs when the radiation damage overwhelms the body's ability to recover. Cancer appears to be a much more probabilistic illness. You develop cancer when you get, by chance, exactly the worst possible kinds of mutations, creating cells that grow and divide and will not be turned off by normal bodily controls.

In fact, we don't really know if the linear hypothesis is valid at low levels (1 rem) of radiation exposure. That's because cancer is a common disease. Even without radiation, 20% of people die from cancer. So with 2500 people, you expect 500 cancers anyway, even with no exposure to radiation. Now let's look at what will happen if each of the 2500 people is exposed to 1 rem.   According to linear hypothesis, we expect *one* additional cancer in the group, i.e. 501 cancers. Statistical fluctuations (discuss in the Appendix B) make such a small effect virtually impossible to verify. Even with large numbers of people exposed (e.g. in the Chernobyl nuclear reactor accident; see the next section) the effect tends to be obscured in statistical fluctuations and systematic uncertainties.

But a premature death from cancer is a tragedy for someone, even if it doesn't appear in the statistics. One additional cancer is significant (especially to the person affected), even if it is not "statistically significant." That's why many people think we should assume the linear hypothesis, even if it is experimentally unverified, and use it as a basis for public policy. Since the linear hypothesis forms the basis for much public discussion, it is important for future Presidents to know what it implies. It is equally important to know that it may not be accurate.

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[10] Cancer appears to require a series of mutations, perhaps three or four. In the linear hypothesis, we assume that many people have already had the required two or three mutation, perhaps from other carcinogens, and only the last required mutation is delivered by the radiation.

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Chernobyl nuclear power plant may kill 24,000 people
(if the linear hypothesis is correct)

In 1986, the Chernobyl nuclear power plant in Ukraine had a violent accident. There was an explosion in the vessel that contained the radioactive fuel, and a huge amount of radioactivity was released into the atmosphere. We'll discuss the innards of nuclear reactors in coming chapters; for now, all you need to know is that a vast amount of radioactive material was released. Several of the firefighters who put out the Chernobyl blaze died from radiation sickness.   Radioactivity from the plant was carried by wind over populated areas. This was one of the biggest news items of the 1980s; everybody who was an adult at that time remembers it. There was fear around the world as the radioactive plume drifted. Some radiation from this event was detected in the United States.

The Chernobyl event was one of the most famous and important events of the entire decade. It was in the newspapers for months. It is cited today by many people, those who oppose the further use of radioactive processes (such as nuclear power), and by those who are in favor of nuclear power.[11] People can find in Chernobyl data that supports their point of view, regardless of what that point of view is. So it is important to understand this event. It would be worthwhile to read more about the Chernobyl accident. You will find many links to the Chernobyl disaster on the Web.

Even though a lot of effort went into mapping the spread of the radiation, most of the damage was done in the first few days, so it is hard to know what was the total exposure to humans. The firemen who died had received several hundreds of rem. Between 25,000 and 40,000 people are thought to have received a median dose of 45 rem. The government decided to evacuate all regions in which a person would receive a lifetime dose of 35 rem or more. The nearby city of Chernobyl fell below this limit. The cloud of debris blew over 1000 miles, towards Stockholm Sweden, giving most people in that city a dose exceeding one rem. There is a map of the areas most severely exposed in the introductory physics text by Hobson. One reasonable estimate is that the total dose to the world population was 60,000,000 rem. This number is obtained by estimating the number of rem received by each person on the Earth and then adding those numbers together.

If we assume that the linear hypothesis is correct, we can now calculate the number of cancers induced in a remarkably simple way: just divide the number of rem by 2500 to get 60,000,000/2500 = 24,000 cancers world-wide.

Now let's calculate the expected cancers for the people near the nuclear plant. Based on the numbers given above, assume 40,000 people received 45 rem on average.[12] Multiply

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[11] Those in favor say that this events shows the very *worst* that can happen.

[12] 45 rem was the median, not the mean, so this is a rough approximation.

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these to get the total dose to these people of 1.8 million rem. Divide by 2500 to find the total number of cancers expected; 720.   (These people were already counted in the 24,000 number.)

This is clearly a great tragedy. And yet, a surprising fact to many people is that even if this calculation is correct, and the number of cancers predicted is accurate, it will be difficult to identify the people who are being killed by the Chernobyl accident. There are too many other cancers.

Let's consider the nearby victims. Among 40,000 people, we would expect 20% to die of cancer anyway. That means 8000 deaths that are not a result of the radiation. On top of these, we predict another 720 deaths from the radiation exposure. So the total cancers, instead of being the "normal" 8000, will rise to 8720. Of these 8720, only 8% were caused by the Chernobyl accident. It is difficult to know which ones are dying from "ordinary" cancer, and who is dying from the radiation effects, unless the kinds of cancer induced by radiation are different. (There are some differences: thyroid cancer is more prevalent, for example, from radiation – although it rarely leads to death.)

In a population of 100 million people (estimated people who received measurable radiation), we expect there to be approximately 20 million cancers from other causes. Let's pretend for a moment that this number is exact: 20,000,000 "ordinary" cancers. Because of Chernobyl, this number will be increased to 20 million + 24 thousand = 20, 024,000. Put another way, the probability of anybody getting cancer, if exposed, has been increased from 20% to 20.02%. Given the natural variations in cancer, most people think that we will not be able to see the increase statistically.

Yet those 24 thousand people are all individuals who otherwise would not have died from cancer. There is a strange paradox here. Tragedy is occurring, and yet is almost invisible among the much larger tragedy of cancer from other causes.

Cancer from Nuclear Bombing of Hiroshima

I stated in the opening paragraphs of this chapter that in Hiroshima, fewer than 1% of the deaths caused by the atomic bomb were from cancer.   The reason is simple: unless you were far from the center of the blast, you were killed by the blast or fire. Many who survived the fireball received enough radiation to die of radiation sickness. The best estimate is that there were about 52,000 survivors (not killed by those other effects) who received 0.5 rem or more; the average dose for these people was 20 rem.   That means that the total dose was 52,000 x 20 = 1,040,000 rem. Divide this by 2500 rem per cancer, to get the total expected number of cancers is 1,040,000/2500 = 416. That is 0.8% of the 52,000 people.

Estimates of the total number of people killed by the Hiroshima bomb vary between 50,000 and 150,000. (It is hard to know how many people were there when the destruction was so total in the core of the city.) But you can see now why the cancer

deaths were less than 1% of this. For additional analysis, see
http://whyfiles.org/020radiation/hiroshima1.html.

Cancer deaths would have been much more significant if the bomb had been exploded when it was close to the ground, rather than at high altitude, because that would have increased the amount of radioactive "fallout." We'll discuss fallout further in Chapter 5, when we discuss the "hydrogen bomb."

High radiation in Denver

Denver is located in a geologic area that emits (from the ground) higher-than-average amounts of the radioactive gas *radon*. A reasonable estimate[13] is that the average yearly excess in Denver (compared to the US average) is about 0.1 rem per person per year. For 2.4 million people, living in Denver for 50 years, this excess amounts to $(0.1)(2.4 \times 10^6)(50) = 10^7$ rem, which should cause 4,800 excess cancers.

So here is another paradox: the actual cancer rate in Denver is *lower* than the average in the US!

How can that be? Does it mean that the linear hypothesis is wrong? Or could there be other effects, even more important than radioactivity, that affect cancer? Can you guess what they are? Do you expect that there would be differences in life style, in eating habits, in exposure to sunlight ultra-violet radiation, in genes? Anything else? Does that mean that someone who moves to Denver lowers his risk of cancer?

In case you are hoping I can give you the answer, I can't. Nobody knows the answer. But there are lots of possible explanations. In the meantime, I would not consider the excess radiation of Denver to be an important factor in a decision to live there.

However, before you buy a house in the Denver area, you might want to measure the radon level, to make sure that you are not buying one of the highly radioactive ones. This is a serious comment; some houses have been measured to have dangerous levels.[14] The Environmental Protection Agency offers guidelines for making such measurements, and commercial devices are available.

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[13] There is an internet site that allows you to calculate the radiation dose you get in different locations around the country: EPA radiation dose site. To convert their answer (given in mrem) to rem, divide by 1,000.

[14] Ironically, the highest level ever measured was in a demonstration house built by the Department of Energy. To save energy, the house was built with recirculating air, and as a result, the radon that leaked into the house from the ground could not easily escape.

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tooth and chest x-rays

You are exposed to radiation every time you get an x-ray photograph taken of you. Such photographs are now called "x-rays" themselves, but that is just short for "x-ray photograph" or "x-ray image." You may have noticed that the person who takes the image leaves the room when the x-ray machine is turned on. For a tooth x-ray, a lead shield may be placed over you body to protect your "vital organs." This frightens many people. What is the danger?

Next time an x-ray is taken, ask the technician for the dose in rem. (Odds are, the technician won't know, but will simply assure you it is safe.) A typical dose for a dental x-ray is less than 1 millirem (i.e. 0.001 rem); for the purpose of the calculation, let's assume the dose is one millirem = 1 mr = 10^{-3} rem.

The numbers that we gave for cancer assumed "whole body dose." That means, they gave the cancer rate assuming that every part of your body got the same dose. But when your tooth and jaw are exposed, it is probably not more than a pound of flesh that is exposed. Let's assume it is 1% of your body. Then, by the linear hypothesis, such an exposure is only 1% as dangerous as whole-body dose. That makes it is equivalent to 1% of a millirem whole body, i.e. to 10^{-5} rem. From the linear hypothesis, it takes 2500 rem per cancer. That would require $2500/10^{-5} = 250,000,000 = 250$ million tooth x-rays. Put another way, one tooth x-ray will induce cancer with the chance of 1 in 250 million, = $1/250,000,000 = 4 \times 10^{-9}$.

Let's now calculate the risk of cancer from a chest x-ray. Modern chest x-rays are about 25 millirem to about 50 lb of your body. That is a much greater dose than you get from a tooth x-ray. It is 25 times more millirem, to 50 times more body, which means the dose is 25x50 = 1250 times greater. The number of cancers per chest x-ray should also be 1250 times greater than for the tooth x-ray. That number comes out $1250 \times 4 \times 10^{-9} = 5 \times 10^{-6}$.

x-rays and pregnancy

Radiation can be particularly dangerous to the fetus. Mutation in one of the stem cells (those cells that turn into other cells) can lead to mental retardation, malformed growth, or cancer. If the mother has a tooth x-ray (or one to her ankle) the danger is tiny.

As with other low dose effects, our actual knowledge of effects is limited, and is based primarily on high-level exposures (e.g. in accidents and WWII) and the linear hypothesis. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has studied this problem, and concluded that the risk to the fetus is about 3% for each rem of exposure.

If a dental x-ray were applied directly to the fetus, the linear hypothesis says that the 1 mrem dose would result in a risk 1000 times smaller, i.e. 0.003% for each mrem. If the radiation is delivered to the tooth, and the only radiation reaching the fetus is 100 times

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smaller, then the risk goes down by a similar factor. It is possible that the dangers of the mother's untreated tooth can be greater to the fetus than these small amounts of radiation.

ultrasound

Many pregnant women are exposed to ultrasound. Although technically ultrasound is a form of "radiation" (as is sound itself), it does not have any of the ability to cause mutation that x-rays or beta rays have. Ultrasound is high frequency sound, and it does not have the capability of delivering enough energy to individual cells to cause mutations.

That doesn't mean that there are not other negative effects of ultrasound. But ultrasound radiation should not be confused with nuclear radiation.

Radiation to cure cancer

This may seem paradoxical, but one of the most effective methods to cure cancer uses radiation. Cancers are not healthy cells; they have been mutated to absorb nourishment and divide rapidly. Because they are specialized for division rather than long life, many cancer cells are more vulnerable to radiation poisoning than are healthy cells. So a common way to treat cancer is to hit it with high levels of radiation.

This is typically done by aiming the radiation right at the cancer. The radiation can enter the body from many directions, but it is focused on the cancer. The focusing is designed to make sure the cancer cells get a higher dose than do the surrounding cells. Cells in the vicinity of the cancer also have their metabolism disrupted, and that can induce radiation illness. The goal is to kill the less resistant cancer cells; other cells get sick, but recover. The difficulty, as with all cancer treatment, is that it is necessary to kill virtually all the cancer cells in order to prevent return of the cancer.

If you know someone who is undergoing radiation treatment, you've seen some of the effects of radiation illness. Radiation treatment is often combined with chemotherapy (cancer cells are also less resistant to poisons) so you cannot always tell which effects are due to which treatments. Maybe for this reason radiation treatment is often confused with chemotherapy. Don't confuse them.

Some people avoid radiation treatment because they fear the side effects. Others avoid it because they fear that the radiation will induce cancer. That argument does not make numerical sense. Compare the tiny risk of an additional induced cancer to the extreme danger of the cancer that is already present. But the fear of radiation is so great that some doctors cannot convince the cancer patient to get this treatment.

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Radiological terrorist weapon

Can a terrorist explode a tank of radioactive material in the middle of a city, and make it uninhabitable for the foreseeable future? This scenario has received a lot of attention in the news. Yet it is harder to do this than you might think.

Assume for the moment that you are a terrorist, and you are designing such a weapon. You want to spread material over a square kilometer. Your goal is to make it so dangerous that people would get radiation illness if they were exposed for an hour. Let's say the bomb will be roughly a meter in size, and will be delivered by a truck. To do this you will have to concentrate the radioactive material by a factor of a million (since a square kilometer contains a million square meters). That means that someone within a meter of the bomb will get a lethal dose in one millionth of an hour, i.e. in 3.6 milliseconds. To avoid that, the person might try to stay 10 feet (3 meters) from the bomb. But that distance would still give an LD50 dose in 36 milliseconds.[15]

To avoid this, the terrorist might try shielding the radiation with lead. A half-centimeter of lead will reduce the radiation by a factor of 3; that's not very much. A full centimeter will reduce it by 9; two centimeters will reduce it by 81. Let's try that. The weight of a 1-meter cube with lead walls 2 cm thick is about 1.6 tons. You could carry that in a truck. It would still give an LD50 dose, at a distance of 10 meters, in 3 seconds.

That doesn't mean that a radiological weapon is impossible. It just means that it is much harder than many people suppose.

Jose Padilla was a Chicago street thug recruited by al Qaeda to build and detonate a radiological bomb in the United States. (I recommend a Google search on his name.) He was captured by the police before he had made any definite plans. But in his trial we learned that al Qaeda had told him to abandon plans for a radiological weapon, and instead use natural gas to blow up some apartment buildings. I think it likely that al Qaeda realized that a working radiological weapon was essentially beyond the means of terrorists, and instead reverted to the method that had devastated the World Trade Center – exploding fossil fuel.

What are the rays, really?

It took many years to figure out what the rays really were. Here are the answers:

Alpha rays are chunks consisting of two protons and two neutrons moving at high velocity. This is identical to the nucleus of a helium atom. Because we know this ray is actually a particle, it is sometimes referred to as an "alpha particle." When they finally

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[15] The radioactivity spreads out over a larger area. The area at a distance of 3 meters is about a factor of 9 greater, so the dose is 9 times lower.

slow down, they usually attract two electrons (either free electrons or ones that were weakly attached to atoms) and form a helium atom. Alphas rays are also called alpha particles, and sometimes just "alphas."

Beta rays are energetic electrons. They are much lighter than particles like alphas, yet they move so fast that they have energy comparable to that of the slower alpha particles. When betas finally stop (after numerous collisions), they usually attach themselves to an atom.

Gamma rays are packets of very energetic light. Gammas travel at the same speed as light (3×10^8 m/sec), but they carry typically a million times as much energy as a single packet of visible light. (We'll talk about light packets, also called "photons", in Chapter 10.)

Neutrons are massive particles like protons, but with no electric charge. Neutron emission is very important in the chain reaction, which we will discuss in Chapter 5. The Neutron Bomb is a nuclear weapon that emits a large number of neutrons. It's purpose is to induce radiation illness in people, while doing relatively little damage to buildings. The ethics of such weapons were hotly debated in the 1970s.

X-rays are the most famous of the radiations, since they have become so important in medicine and dentistry. They are packets of light, like gamma rays, but a factor of 10 to 100 less energetic. They pass through many materials (such as water and carbon), but are quickly stopped by elements with high atomic number, such as calcium and lead. The fact that calcium stops them allows them to be used to look at tooth decay and broken bones. An "x-ray" photograph is actually a shadow of the calcium projected on a piece of film. The character "Superman" could not use his x-ray vision to look through lead, since it is one of the heaviest elements, and therefore absorbs x-rays.[16] Lead is used to protect from x-rays. When you get a tooth x-ray, the dentist will likely put a lead-filled apron over other parts of your body to make sure that scattered x-rays don't reach you.

Cosmic rays are any radiation that comes from space. Cosmic rays consist of protons, electrons, gamma rays, x-rays, and muons – unusual particles that can pass through a hundred meters of rock, and are themselves radioactive. Because of their penetrating power, they have been used to x-ray the Egyptian pyramids.

Fission fragments. These are a particularly dangerous kind of radiation that is emitted when a nucleus undergoes fission, i.e. it splits into two or more pieces. Fission fragments are chunks containing large numbers of protons and neutrons, and they are themselves usually highly radioactive. Their real danger comes from when they stop and then re-

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[16] He would also not be able to look through uranium or plutonium, but I don't think that ever made it into the stories. For some unexplained reason, he was highly allergic to kryptonite, which I presume is a compound containing the element krypton. Maybe that came from too much childhood exposure.

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decay. These are the radioactive particles that make fallout from nuclear bombs so dangerous.

Cathode rays. When it was discovered that "rays" were emitted from hot metal that had high voltage applied, they were called "cathode rays." It wasn't known that the rays were actually electrons -- because the electron hadn't been discovered yet. That had to wait for the 1897 work of J.J. Thomson. Most people still call the device that uses these beams "cathode ray tubes" or "CRTs."   As of the early 21st century, many TV and computer screens are still made of CRTs, but they are quickly disappearing. But (if you are young) your children may never hear this term, since in the near future all CRTs will likely be replaced with thin screens. For more on the history, see:
http://www.aip.org/history/electron/jjrays.htm

Neutrinos. These are the most mysterious of all the rays. They are usually emitted at the same time that beta rays (electrons) are emitted from a nucleus. Neutrinos have such small mass, that even when they have only moderate energy they move nearly at the speed of light. They do not "feel" electric or nuclear forces, so they pass through the entire Earth with only a small chance of hitting anything. They are so strongly emitted by the sun that over 10^{10} of them are passing through every square centimeter your body every second. Nevertheless, they are the least dangerous radiation you are exposed to.

Radiation from cell phones. Cell phones emit microwaves, very low energy packets of light, even lower energy than those of visible light. Microwaves deposit their energy in the form of heat; that's why they can be used in microwave ovens. Microwaves do not break DNA molecules in the body, and therefore they pose no risk of causing cancer in the way that alpha, beta, gamma rays, and even sunlight can. Much of the fear of microwaves comes from the fact that they share the name "radiation" with the other, far more dangerous forms such as gamma radiation.

Smoke detectors

The most common smoke detectors have a small radioactive source underneath the cover. It is typically an alpha particle emitter, with alpha particles that go only about 1 cm in air before they stop. These alpha particles knock electrons off the air molecules, and that makes the air electrically conductive. This conductivity is measured with a battery. If the air is conductive, then the alarm does not sound.

However, if smoke drifts under the cover, then the electrons tend to stick to the smoke particles. That means they are no longer free to move, and the electric current stops. When the electronics detects that electric current is no longer flowing, it sounds the alarm, usually a piercing screech.

Obviously it is important that the battery work. Smoke alarms measure the battery strength, and if it gets weak, the electronics emits short beeps to alert you.[17]

You are radioactive

A typical human body contains approximately 40 grams of potassium. Most of this is the stable (non-radioactive) isotope potassium-39. Each nucleus of potassium-39 contains 19 protons and 20 neutrons, totaling 39 (that's why it is called potassium-39). But about 0.01% of the potassium atoms have an extra neutron in their nucleus, and are called potassium-40. Potassium-40 is radioactive. This means that your body contains $40/10,000 = 0.004$ grams = 4 milligrams of a radioactive cancer-producing isotope. The number of radioactive potassium-40 atoms in your body is 6×10^{19}. This is not an artificial radioactivity, but it is left over from the formation of potassium in the supernova that gave birth to our solar system (more on this later).

Potassium-40 is often abbreviated as "K-40". The K comes from the Latin name "kalium" for pot ashes -- the original source of *pot*assium. Parts of the word kalium also survive in the word "alkali".

Approximately 1,000 atoms of K-40 (read this aloud as "potassium-40") explode in your body every second. Your body is radioactive. 90% of the explosions produce an energetic electron (beta ray); most of the rest produce an energetic gamma ray. So there are about 1000 self-inflicted radiations per second from your own body. This body radioactivity produces a dose of approximately 0.016 rem = 16 millirem in your body over a 50 year period.   If the linear hypothesis is correct, we calculate the cancer induced by dividing the rem by 2500. Your chance of having a self-induced cancer is $0.016/2500 = 6.4 \times 10^{-6}$, i.e. about 6 chances in a million. That's small, although it is higher than your chances of winning a typical grand lottery.

The results are more interesting if you think about the consequences for a large population. There are about 300 million people in the United States. Multiply 300 million by 6 millionths of a cancer per person, and you find that $300 \times 6 = 1800$ people will die of cancer over the next 50 years in the United States, induced by their own radioactivity. That averages to 36 per year in the US. If you sleep near to somebody, then their radioactivity can affect you; see the discussion topic at the end of the chapter.

A second source of radioactivity in our bodies comes from carbon-14, also called "radiocarbon", and abbreviated C-14. The C-14 nucleus is similar to that of the ordinary

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[17] The beeps, in my experience, appear to be on a musical note that is very hard to locate. Typically the beep comes every 10 minutes (so that the weak battery isn't completely drained). I've heard the beep, tried (and failed) to find the smoke detector, and then waited ten minutes for the next beep, tried again, and again…. I finally located the responsible smoke detector on the wall of a closet, but it took about an hour of patience.

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(C-12) nucleus, except that it has two extra neutrons (increasing the atomic weight from 12 to 14). But, it turns out, those extra neutrons makes carbon-14 radioactive. In carbon-14, one of the neutrons will explode, emitting an electron and a neutrino. When the electron and neutrino were emitted, the neutron turned into a proton, so the remaining nucleus is nitrogen. On average, half of the carbon-14 atoms in your body will explode in 5730 years. 5730 years is called the "half life" of C-14.

Every gram of carbon in your body has 12 atoms of carbon-14 exploding every minute, one explosion every five seconds, on average. In an average body, there are about 3,000 such radioactive explosions every second.[18] This is in addition to the 1000 K-40 decays mentioned earlier.

Now here is the really fascinating thing about C-14: we can use it to measure how long things have been dead. To see how this works, we have to understand a very strange phenomenon in radioactive decay that is called the "half life rule."

The mysterious half-life rule

As mentioned above, half the atoms of C-14 decay in 5730 years. It is natural to assume that the remainder would decay in the next 5730 years, but that is not what happens. Only half of them decay in the subsequent 5730 years. And then in the following 5730 years, only half of the remainder will explode. The remaining fractions after various years are shown in the table below:

age of C-14	number of half lives	fraction remaining
5730 yr	1	1/2
11460	2	1/4
17190	3	1/8
22920	4	1/16
5730xN	N	$1/2^N$

The value of the half life is different for different radioactive isotopes, but the behavior is similar. For potassium-40 the half life is 1.25 billion years. In 1.25 billion years, half of the potassium-40 decays. In the next 1.25 billion years, half of the remaining atoms decay. There have been nearly 4 half-lives since the Earth was formed, about 4.6 billion years ago. That's why there is so much potassium-40 left; since the formation of the Earth, there hasn't been enough time for all the potassium-40 to decay.

By the way, did you notice how similar this rule is to the rule we used to calculate the density of air at different altitudes (Chap 3)? Recall that at 18,000 feet altitude, the density of air is half of what it is at sea level. Go up another 18,000 feet, and the density

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[18] This assumes you weight 150 lbs, and are 23% carbon (typical for humans).

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is reduced by another factor of 1/2, and so forth[19]. At 180,000 feet (ten such steps) the density is $(1/2)^{10}$. The math is identical to that for radioactivity!

Radioactive decay

If you have a large number of radioactive atoms, half of them will explode in one half-life. (It may not be exactly half, since the rule is based only on probabilities.) Thus, one half-life later, there are only half as many radioactive atoms. That means that the number of radioactive explosions per second will only be half as great as it was in the beginning. This reduction of radiation was originally called "radioactive decay." But now the word *decay* is applied much more universally. Physicists typically talk about a single nucleus undergoing radioactive decay. In this context, that word is used far more commonly than the word "explosion."

Nuclei die, but they do not age.

The half life rule is true for all the known kinds of radioactivity. But the more you think about it, the more mysterious it is. People don't die following the half life rule. When we are born (at least in the US), we are expected to live about 80 years. If we make it to age 80, we don't expect to live another 80 years -- yet that is the way it would work if our physical aging followed the half life rule.[20] Please appreciate how strange the half-life behavior is! It is as if the atom does not age. The old carbon-14 is identical to the young one. No matter how old it is, it's expected half-life is still 5730 years.

We don't really understand this phenomenon, but physicists sometimes "explain" it by saying that radioactive decay is determined by the laws of quantum mechanics, which are probabilistic laws. For K-40, we say that the probability of decaying in 1.25 billion years is 50%. This probability doesn't change, so no matter how old the atoms is, its probability of decay remains 50% for the next 1.25 billion years. Of course, we haven't really explained anything, because we don't know *why* the laws of physics should be probability laws.

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[19] These numbers are approximate, because the temperature also changes with attitude and that also affects the density.

[20] In fact, at age 80 years, we expect to live, on average, another 9 years.

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TABLE: the half lives of some important isotopes

Polonium-215 --- 0.0018 seconds
Polonium-216 --- 0.16 seconds
Bismuth-212 --- 60.6 minutes
Sodium-24 --- 15.0 hours
Iodine-131 --- 8.14 days
Phosphorus-32 --- 14.3 days
Iron-59 --- 46.3 days
Cobalt-60 --- 5.26 years
Tritium (H-3) --- 12.4 years
Strontium-90 --- 29.9 years
Cesium-137 --- 30.1 years
Radium-226 --- 1,620 years
Carbon-14 --- 5,730 years
Plutonium-239 --- 24000 years
Chlorine-36 --- 400,000 years
Uranium-235 --- 710 million years
Uranium-238 --- 4.5 billion years

Measuring age from radioactivity

Potassium-Argon dating of rocks

If a rock has minerals in it that contain potassium, then it is often possible to tell when the rock first was made. That's because all potassium on Earth contains about 0.01% of the isotope K-40 (potassium-40), and K-40 has a nice property: when it undergoes a radioactive decay, it turns into argon, a gas. This gas then is unable to escape from the solid rock, and it accumulates there. Only if the rock is melted does the gas escape.

To see how that can be used to measure the age of a rock, let's consider a specific example. Suppose we find a rock that is the kind that is formed from lava, i.e. it was once liquid. We would like to know when it turned solid, i.e. when did it become a rock. We look and see if the rock has potassium in it. If it does, then we know that part of that potassium is turning into argon gas. We can see how much argon gas is trapped in the rock, and that way determine how long the rock has been a solid. This technique, called "Potassium-Argon dating" is enormously useful in geology for measuring the age of rocks and of ancient volcano flows.[21]

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[21] I have used potassium-argon dating to measure the ages of craters on the moon. When an asteroid or comet hits the moon, it melts some of the rock. Any old argon in the rock is released. In a few seconds, the rock solidifies again, and begins to accumulate argon from decaying K-40. When we melt the samples in our laboratory, we can measure the amounts of argon and potassium, and from those numbers we can deduce the age.

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"Radiocarbon dating" of old bones

Archeologists can use the radioactive isotope of carbon, C-14, to measure the age of fossils. C-14 is produced in the atmosphere by cosmic rays. It is absorbed into plants when they create carbohydrates out of atmospheric carbon (by "breathing" carbon dioxide). We eat the plants, or animals that ate the plants, or animals that ate the animals that ate the plants…, and that way we get C-14 into our bodies. Since the path from the atmosphere to our bodies happens so fast (typically less than a year) our carbon has nearly the same radioactivity as the atmospheric carbon: 12 decays per minute for each gram of carbon.

When we die, and no longer eat food, the carbon-14 decays and is not replaced. If an archeologist finds a fossil, and measures that each gram of carbon in it is has only 6 decays per minute of C-14, rather than 12, then he knows that creature died one half-life ago, i.e. 5730 years ago. This method is the primary means for measuring ages in archeology.

As another example, suppose the archeologist measures 3 decays per minute. (Remember: 12 per minute indicate an age of zero.) What is the age of the fossil? Careful -- potentially trick question. Try it, and then check the footnote[22] for the answer.

After 10 half-lives, the radioactivity has been reduced by a factor of $(1/2)(1/2)(1/2)(1/2)(1/2)(1/2)(1/2)(1/2)(1/2)(1/2) = 1/2^{10} = 0.001$. So instead of 12 decays per minute, the archeologist will measure only 12 decays per 1024 minutes. Such low rates are very difficult to measure, so C-14 is useful only to ages of about 10 half-lives, i.e. about 57,300 years. Beyond that, the rate is too low.[23]

Puzzle: Why doesn't the carbon-14 in the atmosphere decay away as it does in our bodies?
Answer: It does, but it is constantly replenished by new cosmic rays. The level in the atmospheric carbon is set by the level at which the decay exactly balances the production. That turns out to be one C-14 for every 10^{12} ordinary carbon atoms. And at that density, one gram of carbon (which will have 10^{-12} grams of C-14) will have 12 decays every minute.

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[22] If the age were one half life, we would expect the rate to be 6 decays per minute. After an additional half-life, the rate should be cut to 3 per minute. This matches the observation. So the fossil is 2 half-lives old = 11,460 years.

[23] One way around this limit is to count the remaining C-14 atoms, rather than the number of decays. Even when the decay rate is low, there is a very large number of atoms left. The trick is to find them, but this can be done with instruments known as Accelerator Mass Spectrometers (AMS). The first person to succeed in doing such a measurement was the author of this book.

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Radioactive alcohol

Let's return now to another of the anecdotes that appeared at the beginning of this chapter. In the United States, alcohol for consumption must be made from fruits, grain, or other plants. It is illegal to make it from petroleum. (I don't know why, but it is the law.) Of course, any alcohol made by the fermentation of plant matter contains recent, radioactive carbon-14. In contrast, petroleum was created by decaying vegetable matter that got buried 300 million years ago. A half life is only 5730 years, so the petroleum was formed from living matter that died over 50,000 C-14 half lives ago. There is no detectable C-14 left in it. This absence provides an easy way for the U.S. government to test to see if alcohol was produced from petroleum. The United States Bureau of Alcohol, Tobacco, and Firearms tests alcoholic beverages for C-14. If the expected level of radioactivity from C-14 is present, then the beverage is fit for human consumption. If the alcohol is not radioactive, then it deemed unfit for human consumption.

Environmental radioactivity.

Is all cancer caused by radioactivity in the environment? No. If you live in a typical city, you are exposed to about 0.2 rem of radiation every year. Most of this comes from radon gas seeping up from the rocks in the ground and cosmic radiation coming from space, and some of it comes from medical x-rays, if you get them. In 50 years, the typical American is exposed to a total of about 15 rem of mostly natural radioactivity. To calculate the expected cancer, you follow our rule: take the total number of rem (rem per year multiplied by number of years) and divide by 2500. This gives $15/2500 = 0.004 = 0.4\%$. But 20% of people die from cancer, not 0.4%, so the cancer must be coming from something else.

What else? Some people think it is food, or pollutants, or something else that we might be able to eliminate. But if we add up all known carcinogens, we still can't account for the bulk of cancer. So there is some other cause. It could be something as simple as the natural exposure to the highly reactive chemical known as oxygen – which we can't eliminate unless we give up breathing. Nobody knows.
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Volcanic heat and helium balloons

The rock in the Earth is radioactive, largely from potassium, uranium, and thorium in the ground. If you have ever been in a deep mine, you know it is very warm -- not cold, as it is in a shallow mine or cave. The reason is that heat is gradually seeping up from inside the earth. Uranium and thorium decays underground produce a large number of alpha particles. The underground heat is the energy lost by the alpha particles as they slow down in collisions with other atoms. When the alpha particles finally stop, they pick up electrons and turn into helium gas. This gas collects underground along with natural gas (methane), and is extracted along with the gas. It is what we use to fill helium balloons.

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The total power generated inside the Earth from radioactivity is about 2×10^{13} watts. That sounds like a lot, but the sunlight hitting the Earth has 2×10^{17} watts, a factor of 10,000 greater.[24] So the energy coming down is much greater than the energy coming up.

(For Jupiter, the heat generated in the planet is actually larger than the heat that reaches the surface of Jupiter from the Sun!)

The heat generated underground by radioactivity is responsible for volcanoes, thermal springs, and geysers. Under a large glacier (during the ice ages glaciers were several kilometers thick) the heat from the Earth is enough to melt the ice at the bottom of the glacier, and that keeps it slipping.

The Earth is 6370 km thick (to the center), so it is surprising that 20% of the heat come from radioactivity near the surface, in the "thin" shell of rock known as the crust. The crust is only 30 km thick, on average, but it contains a much higher density of the radioactive uranium, thorium, and potassium. At the bottom of the crust, 30 km down, the temperature of the rock is about 1000 C.

Why aren't most elements radioactive?

This might sound like a silly question, until you learn the answer. We believe that, in the early solar system, most atoms *were* radioactive. There are intensely radioactive isotopes (containing nuclei with a different number of neutrons) of hydrogen, oxygen, nitrogen, calcium, and all the other atoms of which we are made. These were once abundant. But most of them had short half-lives, from fractions of a second to millions of years[25], and as a result, most of them decayed away. Now, 4.6 billion years later, we are left only with three kinds of atoms: those that are not radioactive (e.g. C-12), those that have very long half-lives (e.g. K-40 and uranium) and so haven't yet disappeared, and those that have been produced in the recent past (e.g. C-14).

Optional: the *cause* of radioactivity: tunneling, and the "weak force"

Chemical explosives must be triggered (e.g. gunpowder is exploded by the impact of the hammer of the gun; TNT is usually detonated with the help of an electrical signal). What triggers the nuclear explosion of radioactivity? Alpha decay and fission (to be discussed soon) come from a quantum mechanical phenomena called "tunneling." In tunneling, a particle that is tightly bound to another one by nuclear glue (the gluons) makes a "quantum leap" away, to a location where the force is weak. At this distance, the force

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[24] It is interesting to note that for the planet Jupiter, the heat coming from the interior is greater than the heat coming from the Sun, although this heat is probably generated by the gravitational contraction of the planet rather than from radioactivity.

[25] In the context of the Earth's age, even millions of years is *short*.

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on the particle is dominated by its electric charge, and it is strongly repelled. That repulsion is what gives the particle its high energy.

For beta radiation, the answer is totally different. For many years, it was hypothesized that there was a new "force" in the nucleus that was responsible, a force that was so weak that didn't do anything else except, once in a while, trigger radioactive decay. We now know that this force is real, that it is related to the electric force, and that it operates in such a way that it triggers the explosion. Because of its history, it is called the "weak force." The fact that the force is weak means it has a very low probability of that happening in any one second. It takes 5730 years for a C-14 atom to have a 50% chance of decay.

We now know that the weak force can do more than just cause beta decay. It can also put a force on the particle. The mysterious particle called the "neutrino" has no electric charge. It does not feel a electric forces, but only the weak force and gravity. Despite its name, the weak force on the neutrino is stronger than that of gravity. But when a neutrino goes through the Earth, there is a small but non-zero chance that it will collide with one of the atoms in the Earth, because it can feel their weak force.

There are particles that don't feel the weak force at all. The most important one is the particle called the *photon*. A photon is a particle of light, sometimes called a "wave packet" of light. (We'll discuss these further in Chapter 10.) X-rays and gamma rays are also photons. Photons don't feel the weak force, but they do feel gravity. They pick up energy when falling in a gravity field, and their paths are deflected when traveling close to a massive body like the Sun or the Earth.) Another particle that we think does not feel the weak force is the graviton, a particle consisting of an oscillating packet of gravitational field.

Is radioactivity contagious?

By this, I mean: if you are exposed to something that is radioactive, do you become more radioactive yourself? Do you "catch" it, like you catch a cold?   In the world of science fiction the answer is yes. People exposed to atomic bombs come away glowing in the dark. But in the real world, the answer is no, at least most of the time, for most kinds of radioactivity.

There are two ways that you can become more radioactive by being exposed to radiation. The first is if you actually get some radioactive material stuck on you, or if you breath it in. You don't really become radioactive, you just become dirty with radioactive dirt. This could happen if radioactive debris from a bomb lands on you, or if you touch radioactive dust while taking a tour of the inner parts of a nuclear reactor. (When I did this recently I had to wear special clothing, and I was instructed to touch nothing.)

But there is a kind of radioactivity that really can make you radioactive: neutrons. Some forms of radioactive explosions emit neutrons, and when these hit your body, they can

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attach themselves to your nuclei. For example, if you add two neutrons, you can turn your C-12 nucleus (which is not radioactive) into a C-14 nucleus, which is radioactive. In reality, to do this would require so many neutrons that you would be dead, from radiation illness. But objects exposed to intense neutrons do become radioactive.

Forensic radioactivity: "Neutron activation"

Radioactivity is unique in its ability to detect a tiny number of atoms hidden amongst a vast number of others. In your body, only one carbon out of 10^{12}, i.e. only one per trillion, is radioactive. Yet we can count the number from the decays, because they emit such energetic particles. Suppose you wanted to detect an atom that is not radioactive? Then the trick is to make it radioactive by hitting it with neutrons. If it makes a unique radioactive isotope, then its presence can be measured.   This clever technique is called "neutron activation" and it is a very useful way to detect elements and their isotopes that are present at tiny (part per billion and less) amounts. Such rare constituents can sometimes be used as "fingerprints" to identify the factory in which an object was made, or the part of the world where it came from.

To activate a sample, it is placed in a nuclear reactor, which bombards it with a large number of neutrons. The sample is removed, and its radioactivity is measured to look for the characteristic rays for the desired element.

This method was used by Luis Alvarez and his team, in 1977, to search for the rare element iridium. They found enough iridium to conclude that it must have come from an extraterrestrial impact (since meteors, comets, and asteroids contain abundant iridium) and from this discovery, concluded that a large impact had taken place 65 million years ago – at the very time that the dinosaurs went extinct.

The glow of radioactivity

Objects that are intensely radioactive can cause the surrounding air to glow. That's in part because the radiation can knock electrons off the air molecules, and when those electrons re-attach, they emit light.   Likewise high energy electrons can cause water to glow. But such a glow is usually seen only at levels of radiation that are extremely high, such as found inside a nuclear reactor.

Even weak radiation can cause strong light emission if it hits special materials called phosphors. In a phosphor, even weak rays have their energy absorbed by the molecules of the phosphor. A short time later the atoms release this energy in the form of ordinary light.

The front of a TV screen is made of red, blue, and green phosphors. Take a magnifying glass up to a color TV screen, and look at it. You will not see any white phosphors -- only red, green, and blue. These phosphors, despite their name, are not made of phosphors but of other materials. When the phosphors are hit by electrons (cathode rays)

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they emit light, and that is what creates the image.   If you put a radioactive material near your TV screen, the rays emitted from it would also make the TV screen glow - provided that they can get through the thick glass.

Radioactive watches and luminous dials

Before the dangers of radioactivity were completely recognized, watches had their dials painted with a combination of phosphor and the radioactive element radium. They glowed brightly in the dark. They also gave people cancer, particularly the workers who painted the dials (and licked their brushes to straighten the fibers). It is not legal to make watches with radium dials anymore, although you can sometimes find one at a flea market.

Not all radioactivity is equally dangerous. I would NOT wear a watch that contained radium; the dose to my wrist would be too high. But I do wear a watch that contains tritium (H-3), the radioactive isotope of hydrogen that has a half-life of 12 years. The tritium emits beta rays, and when these hit the phosphor on the dial of the watch, the phosphor glows. In 12 years, unfortunately, my watch will glow only half as brightly.

The low energy electron (beta particle) emitted when tritium decays has so little energy that it stops within a few thousandths of a centimeter. So it never gets out of the watch. It goes only far enough to make the phosphor emit light.[26]

Tritium watches have not sold very well because people confuse them with radium watches.

Plutonium

Small particles of radioactive material, such as plutonium, can be very dangerous. Even a tiny dust mote can contain 10^{14} plutonium atoms. If you were to breathe in a large number of such particles, and they got lodged in your lungs, then one small region of your lungs could receive large doses by having billions of nuclei decay at the same spot. This is why people worry about plutonium. It has been called "the most poisonous substance known to man." That is incorrect, and a bad exaggeration, but when you hear it said (and you will), you will know that the origin of the fear is the possibility of small particles lodged in your lungs. Plutonium is less toxic than, for example, botulism toxin. Large pieces of plutonium are much less dangerous -- unless they are used to make a nuclear bomb.

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[26] Some day we may have computer screens illuminated with tritium. Right now it is too expensive; and most people mistakenly fear *anything* that is radioactive, so people haven't built factories to make tritium cheaply. But with a tritium screen, it would be on all the time, with no battery needed. Of course, after one half-life (about 12 years), the screen would be only half as bright, assuming you still owned the same computer 12 years later.

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The author's mentor, Luis Alvarez, used to keep a piece of plutonium on his desk, as a paper weight. (That was when he worked at Los Alamos, on the atomic bomb project.) Why didn't the plutonium cause cancer in his hand? The reason is that the radiation from plutonium consists of alpha particles that slow down rapidly when traveling through matter. They will be stopped by piece of paper. So although the alpha particles enter the skin, they enter only the outer layers of skin, which are either dead already, or soon to be shed. (The primary way that skin protects itself from carcinogens is by constantly shedding its outer layers, and replacing them with fresh skin from underneath.) In contrast, in the lungs the live cells are in contact with the atmosphere. That is also why lungs are so vulnerable to cancer from smoke, whereas the skin is not.

Some people have suggested that terrorists might make a plutonium bomb, not a nuclear explosion, but just one that will take a piece of plutonium blow it into small particles that could get into the lungs. That is possible, in principle, although getting a metal into particles of the right size is very difficult to do. A terrorist might kill more people if he were to make a botulism toxin bomb instead of plutonium one. And botulism toxin is much easier to obtain. (It often appears in home-made mayonnaise if the mayonnaise is not kept properly cool.)

Fission

Fission refers to a special kind of radioactivity: the sudden splitting of a nucleus into two or more large parts. It was named in analogy to the fission of biological cells. Fission occurs in two forms: spontaneous and induced. Spontaneous fission is almost non-existent in nature.[27] It does occur in some artificially produced isotopes.

In spontaneous fission, the nucleus behaves like other radioactive nuclei: it sits around unchanged for typically one half life, and then at some random time it decays by suddenly flying into pieces.

A second kind of fission is *induced* fission. This kind is far more important for this book. Induced fission can occur if the right kind of nucleus is hit by a neutron. The neutron is absorbed, and the resulting nucleus, even with just this one tiny addition, becomes unstable, and fissions. This kind of fission is the fundamental basis of both nuclear reactors and nuclear weapons (the "atomic bomb"). We'll discuss induced fission in more detail in Chapter 5.

When a nucleus breaks fissions, the bulk of the mass is usually divided into two unequal pieces called (appropriately) *fission fragments*. These pieces are usually radioactive with relatively short half lives (from seconds to years), and they can be very dangerous to humans. They are the primary source of the residual radioactivity after a nuclear weapon has been exploded.

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[27] The radioactivity of natural uranium is primarily alpha emission. However, one in about 20,000 of the decays is spontaneous fission.

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Fusion

Fusion is the source of energy for the Sun, and as a consequence, it is the ultimate source of energy for virtually all life on Earth.[28]

When Charles Darwin published his Origin of Species, he had a lot to say that went beyond evolution. He had found fossil sea shells high up in the Andes mountain ranges, and had concluded that these regions had once been under the sea. He estimated that the Earth must be at least 300 million years old, based on his calculation that it would have taken that long for erosion to create some of the great valleys in England. That was adequate time, he concluded, for natural selection to account for changes in species.

But when his book was first published, the great physicist William Thompson, later knighted as Lord Kelvin (after whom the Kelvin temperature scale is named) objected. He told Darwin that the Earth could not possibly be that old, or the sun would have completely burned out. Even if the Sun were made completely out of coal, it would have used up all its energy long ago. A more energetic source, Kelvin suggested, was meteors! (Even Kelvin knew that meteors carried much more energy than coal.) Kelvin estimated that meteoric heat could account for a solar lifetime as long as 30 million years. But 300 million years was not possible, at least according to all the physics known at their time.

Darwin had no answer. In the second and later editions of his book, he removed his thesis that the Earth was hundreds of millions of years old.[29]

Of course, we now know that Darwin's original conclusion was correct. The Earth is about 4,500 million years old. The Sun has been burning for longer than that. It isn't coal that provides the energy, or meteors, but nuclear reactions. But the source is not radioactivity, or even fission. It is a kind of nuclear reaction that we have not yet discussed: fusion.

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[28] We now know that there are colonies of life under the sea that live off the energy of deep sea "vents." These derive their energy from the radioactivity of the Earth's crust, and so there is some life on Earth that survives independently of the Sun. (Although if the Sun weren't there to warm the Earth, the oceans might freeze.)

[29] **Amusing digression**. There is no universal agreement in professional publications on how to refer to "The Earth." Some people point out that we don't refer to "The Mars" or "The Jupiter", and that "Earth" is a proper name, just like Mars and Jupiter. So some people always say "Earth" without the "the", as in the sentence: "The age of Earth is about 4.5 billion years."

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Power from the Sun

"Fusion" refers to the coming together of particles, in contrast to "fission" which is the separation of particles. It may seem strange that you can get energy by bringing particles together, but it is true, if you pick the particles correctly. The basic source of fusion in the Sun comes from bringing together 4 hydrogen nuclei to make helium. In the process, other particles are also created. In a typical solar fusion, in addition to the helium we will get 5 gamma rays (for which we use the symbol γ), two neutrinos (symbol ν), and two positrons (symbol e^+). (A positron is just like an electron, but while the electron has a negative electric charge, the positron has a positive charge). In symbols, we write solar fusion as:

$$4\,H \dashrightarrow He + 2\,e^+ + 2\,\gamma + 2\,\nu$$
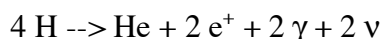
You can read this formula as: 4 hydrogens *go to* (that's the arrow) one helium, 2 positrons, 2 gammas, and 2 neutrinos. Most of the energy is in the positrons, gammas, and neutrinos, not in the helium.

Isn't that fission? Notice that there are more particles after the reaction than before. So why is this called fusion, rather than fission? There is no really good reason for this name. It is really based on the convention that a new element has been created, helium, that is heavier than any of the nuclei that we started with (which were all hydrogen). In fission, the elements created (the fission fragments) weight less than the original uranium or plutonium.

Energy from fusion

It is all the light particles (e^+, γ, ν) that carry most of the kinetic energy. The neutrino (ν) escapes out of the Sun, but the other particles collide with other atoms (mostly hydrogen), share their energy with these atoms, and heat the sun. It is this radioactively-induced heat that makes the sun shine. The energy released in one fusion reaction is typically 25 MeV.

What is an "MeV"? Let's begin with the unit called the "electron volt", abbreviated "eV" (small e, capital V[30]). The eV is useful when talking about individual atoms, since chemical reactions typically have an energy between 0.1 and 10 eV.   An MeV is a million eV. Here are some conversions that I recommend you not bother to memorize: 1 eV = 1.6×10^{-19} joules = 3.8×10^{-23} Calories. One "mole" of material has 6×10^{23} atoms. In chemical reactions, if each atom releases 1 eV of energy, then the energy released is 3.8×10^{-23} x 6×10^{23} = 23 Cal per mole.

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[30] The V is often capitalized, presumably because it arises from a person's name, Volta. (Yet the word "volt" is often not capitalized, which goes to show that there are no absolute rules followed.)

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To compare this with previous work: our table in Chapter 1 shows that methane, burned in air, releases about 13 Cal of heat per gram. One mole of methane is 16 grams, so methane releases 13x16 = 208 Cal per mole. That's about 9 eV per molecule.

Why the world is interesting

Sun is a star, and the fusion that takes place in Sun is very similar to the fusion that takes place in stars. If the only fusion that took place was the combining of 4 hydrogens into one helium, then the world would be a very dull place. The reason is that complex life, as we know it, requires heavier atoms such as carbon and oxygen. Not much of interest (life, intelligence) can happen when all you have is hydrogen and helium. The only molecules you can get is H_2. Carbon makes very complicated molecules (such as DNA) and that makes interesting life possible.

We believe that the heavier atoms such as carbon and oxygen are created inside stars. Carbon is formed from the fusion of three helium atoms. All the carbon in you body, all the oxygen in the atmosphere, was once buried deep in a star, where it was created. Fortunately, for those of us who like an interesting world, that star eventually exploded, spewing its debris into space. Eventually the material clumped up to form a new star (which we call the Sun) and a bunch of planets (Earth, Venus, Mars, etc.). With all the carbon and oxygen on the Earth, life (as we know it) was possible. We are literally made out of the ashes of an exploded star. The Sun is a secondary star, created from such debris of an earlier star.
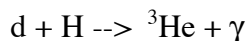
Optional: the details of fusion

You don't have to know the contents of this section, unless you are interested. The fusion reaction that we gave above, with 4 hydrogens turning into one helium and a bunch of other things, does not usually take place in just one step. If the star is a primary star, made of only hydrogen and helium, then the first step is that two hydrogens will combine to form a deuteron (nucleus contains one proton and one neutron), a positron, and a neutrino. In symbols, the reaction looks like this:

$$H + H \longrightarrow d + e^+ + \nu$$
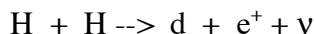
Even though the formula shows hydrogen as "H", it normally takes place in such a hot place that its electron has been knocked off, i.e. it is a plasma. Thus the hydrogen in the equation is really just a proton. The electron, moving in the plasma, doesn't take part in the reaction.

Then the deuteron combines with a Hydrogen to create an isotope of helium called "Helium-3" and written as ^3He:
$$d + H \longrightarrow {}^3He + \gamma$$
Finally, two Helium-3 atoms combine to form ordinary helium:
$$^3He + {}^3He \longrightarrow He + 2\,H + \gamma$$

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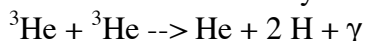
Note that in the end, the original hydrogens have been transformed into helium plus a few other things.

Why isn't the Earth a star?

Why doesn't fusion take place on the surface of the Earth? Or inside a tank of hydrogen gas? The simple reason is that they aren't hot enough. Why does that matter?

The nuclei of all the elements have protons and neutrons in them. The protons give them a positive charge. Positive charges repel, as we will discuss in more detail in Chapter 6. In ordinary matter, two nuclei will never get very close, because of this repulsion.

To overcome the repulsion, you have to give the nuclei enough energy that they are not stopped by the electric force. Energetic atoms are hot atoms. So if you heat the atoms enough, they will have enough kinetic energy to allow their nuclei to overcome the electric repulsion and touch. The temperature that you need depends on the specific fusion reaction, and how often you need to have the fusion take place. The temperature in the center of the sun is believed to be about 15 million K. That's hot, but not too hot. Even at 15 million C what takes place is a relatively slow fusion; most of the hydrogen fuel has not yet burned. Some stars, which are hotter, completely burn out in a few million years, and that doesn't give planets around them enough time for interesting life to evolve.

If we are going to use fusion to generate electricity, then we need hotter temperatures so that the fuel will burn quickly. The plans for controlled thermonuclear reactors (CTR, in the jargon of the energy business) have temperatures of 100 million C.

If you want the reactions to take place in a millionth of a second (to make a hydrogen bomb), then the temperature must be even greater.

How did the Sun get hot enough to ignite fusion?

Of course, the Sun is very hot now, because of the fusion that is taking place. But how did the Sun get hot in the first place? We believe it was simply the gravitational attraction of the matter that made up the Sun. When all that matter got pulled together, the mutual gravity gave it kinetic energy; when it all settled, that energy was converted into heat. This will happen only if the object is big enough so that the temperature rises over a million C. If the mass isn't that large, then the fusion isn't ignited, and the object never turns into a star. In fact, the definition of a star, used by most astronomers, is an object that is large enough that the heat at the core ignites fusion.

The outer surface of the sun is not that hot. It's temperature is about 6000K. That is not hot enough for fusion. All of the fusion takes place at the core of the sun. The heat works its way out, and the surface then glows at a much lower temperature.

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Jupiter is not quite big enough to become a star. It's mass is about 0.1% of the Sun's.   It is believed that to become a star (i.e. to ignite fusion), an object must be substantially larger, about 8% of the mass of the sun, almost 100 times more massive than Jupiter.

Back to the beginning

Look at the anecdotes that opened this chapter. Do they seem less surprising now? If they were surprising when you first read them, why?

<div align="center">END OF CHAPTER</div>

Quick review

Radioactivity is the explosion of the atomic nucleus, the small core of the atom that has only 10^{-5} of the atomic radius, and 10^{-15} of its volume, but over 99% of its mass. The pieces that shoot out from this explosion are called "rays" or "radiation." Important kinds of radiation include alpha particles (2p2n), beta particles (electrons), and gamma rays (bundles of energetic light).

The nucleus has over 99% of the mass of the atom, but only 10^{-5} of the radius, and 10^{-15} of the volume. It is made primarily of protons and neutrons, which are in turn made of quarks. The name of the element is related to the number of protons. Different isotopes of the same element have different numbers of neutrons.

When radiation passes through matter, it breaks apart molecules and knocks electrons off atoms, leaving charged particles called ions. The track of ions can be made visible in a cloud chamber, or (if the material is a phosphor) by emitted light.

The path of damage done by radiation can cause radiation sickness, if it is sufficiently intense. The LD50 for this is 300 rem, and each rem would take about 2 billion gamma rays per square centimeter. At lower levels, the main damage is to DNA and the possibility of inducing cancer. The linear hypothesis states that the number of cancers depends only on the rem dose, and not on the number of people who share this dose. In this picture, about 2500 rem cause one cancer. The linear hypothesis has not be tested for low doses. If it is correct, then the Chernobyl nuclear accident will kill about 24,000 people from cancer. Those people will not be easily identified, since about 20% of people die of cancer from other causes.

Most natural material, including your body, is radioactive from K-40, C-14, and other natural materials. This fact can be used to estimate the ages of rocks and bones. Radioactive decay follows the half life rule: every additional half-life (5730 yrs for C-14), another half of the nuclei will decay. Nuclei die in this way, but until they do so, they do not age. This is one of the mysterious behaviors that comes from quantum mechanics. Radioactivity comes about when the "weak force" momentarily overcomes the strong force,

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Natural radioactivity in rock is the source of heat within the Earth, including that responsible for volcanoes. Alpha particles emitted by K-14, uranium and thorium, slow down, attract electrons, and become helium atoms – used in toy balloons.

We believe that originally, when the sun was formed, that most elements were made up of radioactive isotopes. The radioactive ones have now mostly decayed, so we are left primarily with those that are not radioactive.

The two main causes of radioactive decay are tunneling (a kind of quantum leap), and the weak force. The ghost-like particles called neutrinos are sensitive only to the weak force and to gravity. They are so strongly produced by the Sun that over ten billion of them pass through each square centimeter of your body every second.

Most radiation does not make the material it hits radioactive, with the exception of neutrons. The radioactivity that neutrons induce can be used to find trace amounts of rare materials such as iridium (used to understand the dinosaur extinctions). Plutonium is a man made radioactive element. The main isotope, Pu-239, has a half life of 24,000 years. It is used in nuclear bombs and reactors. It is toxic, but not quite as much as other chemicals including botulism toxin.

Fission refers to the breakup of a nucleus into two or more large parts. Although it happens naturally, the usual method is to induce fission with neutrons. Fission is used in nuclear reactors and in uranium and plutonium bombs. Fusion refers to the coming together of nuclei to make a larger. Fusion usually produces many small pieces too. Fusion of hydrogen into helium produces the energy that drives the sun. Most of the heavier elements (including carbon, nitrogen, and oxygen), the elements that make life "interesting", were created by fusion within a star. Fusion usually takes high temperatures to get started, but then it produces enough heat to keep the process going.

DISCUSSION TOPICS

Linear hypothesis. What do you think about the linear hypothesis? If the deaths aren't observable, should they be counted, even if the linear hypothesis has a good basis in theory?

 Hidden deaths. "If a tree falls in the woods, and nobody ever observes it (or its consequences), did it happen?" That is a favorite quandary of philosophy students. Some people argue that since deaths from very small levels of radioactivity cannot be detected, statistically, that therefore they might as well be ignored. Do you agree?

The danger of double beds. Of course, we can't get away from our own radioactivity. But think about double beds. If we spend a lot of time very close to someone else, we are exposed to their radioactivity as well as our own. Suppose we spend 1/3 of a day in close proximity to another person. Then we might expect to *increase* our potassium-induced cancers by about 1/3, or about 13 per year. Actually, only their gamma rays will reach you; the beta rays (electrons) will stop in their own bodies. The gamma rays are 10% of the radiation, so the potassium-induced cancers will only be about 1 per year. So if

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everyone in the US slept in double beds, the number of additional cancers expected in the next 50 years is 50.

That may sound silly. But remember, those are 50 people who otherwise would not die of cancer. And that's just in the US. The current world population is about 6 billon people, 20 times larger than that of the US alone. So over the world, we expect not 50 deaths from double beds, but 1,000.

Do you think we should do something about the double bed crisis? In the 1950s, many married couples slept in twin beds. (See a replay of any 1950s situation comedy for evidence. If they ever show the bedroom, it will have twin beds.)
Should we return to twin beds? We could instead install shields between people that protect them from each other's gamma rays.
At what point is it silly to worry? What level of "additional cancer" would you consider to be negligible? Would you accept a different level of risk for yourself than you would allow for the entire US? A risk of 0.000006 sounds negligible for me, but 500 preventable cancers in the US sounds substantial -- yet they represent the same numbers! This is at the heart of a fundamental paradox for public policy, and I don't have the answer. (It is also a great opportunity for a demagogue looking for something to use to scare people.)

Lying with statistics. If I wanted to scare you, I quote 13,000 deaths from double beds. If I wanted to make you feel the risk was negligible, I would tell you that the chance of you getting cancer from sleeping in a double bed are 0.000002. (That number is 0.000006 divided by 3.) Both numbers are correct. So be wary when you hear frightening statistics; see if there is a way of stating them that might lead to a different conclusion.

Cancer rates. The cancer rate in Denver is lower than in Berkeley. Some people have argued that this shows radiation protects you from cancer. Is this valid? Why not?

Public perception. Think about a person who lived so near the Chernobyl accident that he received a dose of 100 rem, and then contracted cancer. 100 rem gives a $1/25 = 4\%$ chance of cancer. Therefore his chance of getting cancer had been increased from 20% to 24%. But what is the public perception? Will the friends and relatives believe that the cancer was induced by the accident, even though only one out of 6 (i.e. 4 out of 24) of such people actually had their cancer triggered by the radioactivity rather than by the usual causes?

Radiation and Cancer. Khidhir Hamza was the chief Iraqi bomb designer, before he defected to the U.S. He wrote a book about his experience, called "Saddam's Bombmaker" (with Jeff Stein; Scribner, 2000). In it, he says (page 246):

"The Russian reactor was also targeted. Somebody must have closely studied its layout, because the reactor was destroyed, though not the fuel in the core. (Later, Saddam would claim to UN inspectors that it was destroyed.) The next day, stupidly, tragically, senior

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scientists and engineers were called in to salvage the computers and electronic equipment, and found themselves wading through radioactive water. Many of them, including Basil al-Qaisy, one of the best electrical engineers in Iraq, would eventually come down with cancers."

Discuss this paragraph in view of what you know. Did Saddam's chief bombmaker make a mistake?

Ethics of the neutron bomb. Suppose we had developed the neutron bomb in World War II, instead of the ordinary atomic bomb. The neutron bomb kills people, but does much less damage to buildings. But also suppose that years later, the military invented a bomb that did both -- the "atomic bomb."   And President Carter decided that the atomic bomb, because it did more damage, would be useful to deter war in Europe.   Would the public have decided that that Carter did the right thing, that replacing the neutron bomb with one that did more destruction, was more humane? Some people would argue that this conclusion is the logical consequence of the criticism of the neutron bomb. What do you think?

Short questions

Energy in the Sun is produced primarily by
        ( ) fossil fuels
        ( ) neutrinos
        ( ) fission
        ( ) fusion

A major reason that your body is radioactive is
        ( ) it is slightly contaminated by debris from nuclear tests
        ( ) it is made radioactive by medical x-rays
        ( ) you breathe radioactive carbon from the air
        ( ) you are hit by neutrinos from the sun

Wine made from fossil fuels is not radioactive because
        ( ) the radioactivity has decayed away
        ( ) there is no carbon in such wine
        ( ) ancient plants never were radioactive
        ( ) the half life of the key elements is too long

The primary cause of death from the Hiroshima bomb was
        ( ) radiation induced cancer
        ( ) the blast from the bomb
        ( ) fallout from the bomb
        ( ) smoking induced by fear of the bomb

If the half life of an element is big, that means it
        ( ) decays faster than one with a small half life

-

( ) decays slower than one with a small half life
( ) belongs to a very heavy element
( ) emits lots of neutrons when it decays

Surprising effects of radioactivity include
( ) energy for volcanoes
( ) helium for toy balloons
( ) heat for geysers
( ) all of the above

Muller wears a watch with tritium in its hands because
( ) he is not worried about radioactivity
( ) tritium is not radioactive
( ) the levels of radiation that emerge are safe
( ) no radiation emerges from the watch hands

After three half lives, the fraction of nuclei remaining is
( ) 1/2
( ) 1/4
( ) 1/8
( ) 1/16
The mass of the nucleus is closest to
( ) 99% of that in the entire atom
( ) 1% of that in the atom
( ) 10^{-5} of that in the atom
( ) 10^{-15} of that in the atom

Most of the elements on Earth were created
( ) in the first few million years of the Earth's existence
( ) within a star
( ) in the Big Bang
( ) in a supernova explosion

Fission fragments are
( ) harmless particles emitted in radioactivity
( ) among the most dangerous kind of radiation
( ) ghost-like particles that pass through the Earth
( ) the source of most energy in the Sun

Watch dials containing radium glow because
( ) radioactivity creates light
( ) batteries supply energy when a button is pushed
( ) the dials also contain a phosphor
( ) They don't glow. Only tritium glows.

Mark all the items that derive from radioactivity:

-

( ) helium for children's balloons
( ) volcanic lava
( ) warmth in deep mines
( ) most cancer in the United States

After four half-lives, the surviving tritium atoms are removed. Compared to completely new tritium atoms, they are expected to live:
( ) 1/8 as long
( ) 1/4 as long
( ) 1/2 has long
( ) exactly as long

The fraction of the US population that dies from cancer is typically
( ) about 1 in 10,000
( ) about 1 in 100
( ) about 1 in 5
( ) most of us die from cancer

The "linear hypothesis" is (mark all that are correct):
( ) known to be true
( ) widely used even though it is not proven
( ) known to be false
( ) generally ignored in analysis of radiation deaths

It takes a larger dose of radiation to cause
( ) radiation poisoning
( ) cancer
( ) they are very close in amount needed

LD50 refers to a
( ) lethal dose
( ) legal dose
( ) large dose
( ) lowest dose

One rem of radiation dose takes how many gammas per square centimeter?
( ) about 1
( ) about 5000
( ) about a million
( ) about 2,000,000,000